ABSTRACT

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I. DETERMINATION OF RELATIVE BRIDGEHEAD CARBONIUM ION STABILITIES BY MASS SPECTROMETRY: 1-NORBORNYL vs 1-HOMOCUBYL

II. MASS SPECTRA OF CUBANE DERIVATIVES

Advisor: Dr. Thomas W. Cole, Jr.

Thesis dated May, 1978

Part I of this thesis describes an attempt to use mass spectrometry as a physical tool to determine the relative stabilities of bridgehead carbonium ions. An index of relative carbonium ion stability was obtained based on the relative intensity of the $[M - Br]^+$ vs. $[M^+]$ ions for a series of aliphatic alkyl bromides. The method works very well for simple alkyl bromides, but is not applicable to strained bridgehead bromides where the incipient bridgehead cation is so strained that rearrangement to a more stable species predominates in the initial fragmentation process.

Part II describes the major fragments of certain mono- and disubstituted cubane derivatives.

I. DETERMINATION OF RELATIVE BRIDGEHEAD CARBONIUM ION STABILITIES BY MASS SPECTROMETRY: 1-NORBORNYL vs 1-HOMOCUBYL

II. MASS SPECTRA OF CUBANE DERIVATIVES

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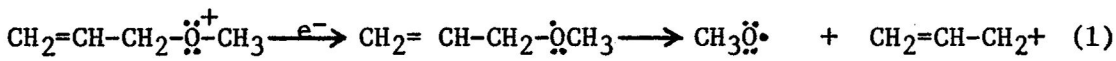
PART I

DETERMINATION OF RELATIVE BRIDGEHEAD CARBONIUM ION STABILITIES BY MASS SPECTROMETRY: 1-NORBORNYL vs 1-HOMOCUBYL

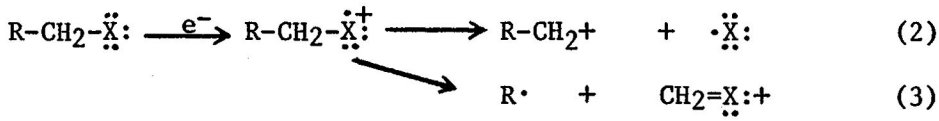
INTRODUCTION

Positive ion mass spectrometry, in a sense, is based on relative carbonium ion stabilities. The general stability sequence of carbonium ions, $R_2C^+ > R_2CH^+ > RCH_2^+ > CH_3^+$ pertains during most fragmentation processes.[1] In mass spectrometry, the molecular ion, M, is a cation radical which usually fragments to produce a cation and a radical. For example, allyl methyl ether would be expected to give rise to the resonance stabilized allyl cation very easily as the major fragment on electron impact.



(1)

In alkyl halides, cleavage with charge retention by the heteroatom fragment usually gives rise only to small or negligible peaks. For bromides, this is negligible for all but low molecular weight compounds. Thus, the process shown in equation 2 is preferred over the α-cleavage of equation 3. Generally, the molecular ion abundance in alkyl halides increases as the electronegativity of the substituent halogen atoms is decreased.[2] This ion is reduced in intensity as the size of the alkyl group is increased or where there is extensive chain branching. Ions formed by α-cleavage containing bromine can be easily recognized due to the characteristic isotopic pattern for bromine. Thus, process (2) can be distinguished from (3) without difficulty.



(2)

(3)

Loss of bromide radical from the molecular ion of alkyl bromides gives the corresponding cation which is usually the base peak in most mass spectra of simple alkyl bromides. To the extent that the initial fragmentation process is the same, measurement of the [M - Br]/[M] ratio could be used as an indication of relative carbonium ion stability. Tertiary-butyl bromide, for example, gives an [M - Br]/[M] ratio greater than 1000. Similarly, 2-bromo-2-methylbutane shows a ratio of approximately the same magnitude. Table 1 lists ratios for these compounds as well as those for several primary and secondary bromides.[3] The reported ratios range from 1-25, 25-500, $\geq$1000, for primary, secondary, and tertiary bromides, respectively. Bromides that yield large peaks from loss of H-Br were not included. 1-Bromoheptane gave the lowest ratio. Thus, with few exceptions, the trend of carbonium ion stabilities parallels the relative intensity of the ion formed from loss of a bromide atom as measured by the [M - Br]/[M] ratio.

A correlation of mass spectral fragmentation with carbonium ion stability has also been reported by Dejongh and Shrader.[4] The spectra of exo- and endo-norbornyl bromides show the typical decomposition and are identical except for the intensity of the molecular ion peak, $C_7H_{11}Br^+$-[M], relative to that of the base peak, $C_7H_{11}^+$[M - Br]. Based on the kinetic approach to mass spectrometric analysis,[5-8] the rate of formation of $C_7H_{11}^+$ from $C_7H_{11}Br$ should be proportional to the ratio of their recorded intensities. The measured ratios of [M - Br]/[M] are 264 for exo- and 26.4 for endo- which gives a ratio of rate constants for the formation of $C_7H_{11}^+$ as 10:1. The fact that exo-bromide is lost faster than

endo-bromide represents a striking correlation with solvolytic studies. Dejongh and Shrader also studied the mass spectra fragmentation of exo- and endo-8-bromobicyclo[3.2.1]octane and observed a qualitative correlation between solvolysis rates and loss of exo-bromide which

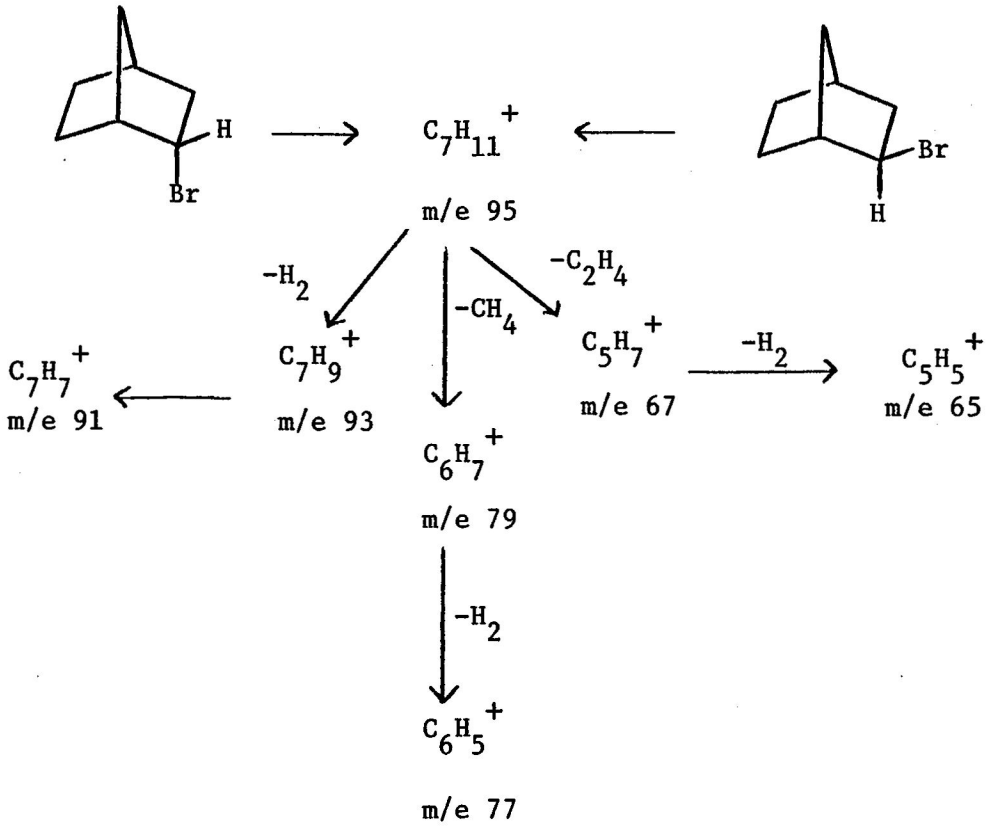
Table 1. Ratio of [M - Br] to [M] for Some Selected Alkyl Bromides.[a]

NAME	[M - Br]/[M]
Bromoethane	0.6
1-Bromopropane	4.4
2-Bromopropane	4.4
tert-Butylbromide	1000
1-Bromobutane	7.7
2-Bromobutane	125
1-Bromo-2-methylpropane	33
Neopentylbromide	2.75
1-Bromo-3-methylbutane[b]	6
1-Bromopentane	10
1-Bromo-2-methylbutane	20
3-Bromopentane	104
2-Bromopentane	207
2-Bromo-2-methylbutane	1000
1-Bromo-3-methylpentane[b]	10.5
1-Bromohexane	25
iso-Hexylbromide	60
3-Bromohexane	435
2-Bromohexane	450
1-Bromoheptane	1
3-Bromoheptane	270

a Data taken from reference 3.
b Large M - HBr

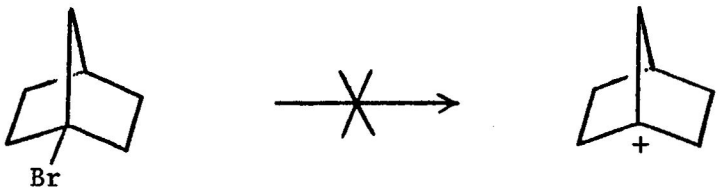
occurred faster than loss of endo-bromide.[7] Fragmentation of the norbornyl bromides is shown in Scheme I.

SCHEME I



It is well known that while tertiary-butyl bromide undergoes facile loss of bromine in solvolysis reactions, bridgehead compounds like 1-norbornyl bromide (1) are completely unreactive under the same reaction conditions. The difference in reactivity can be traced to the relative stabilities of the carbonium ion following ionization. Whereas the triethyl carbonium ion can assume a completely planar geometry as required by the sp^2 hybridization, the bridgehead cation in the bicyclic system (2) can not become planar. If planarity can not be achieved, the stability of the cation is greatly diminished. In the 1-norbornyl system, the most important contribution to the destabilization of the cation is

the increased angle strain following ionization.[8]



1 2

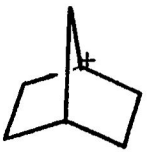
The lower limit of bridgehead reactivity in carbonium ion reactions is usually assigned to the 1-norbornyl cation (2). Of the bridgehead systems most often reported (Table 2), 1-norbornyl derivatives solvolyze slowest in comparison to tertiary-butyl compounds.[9] The homocubyl ion 3 is structurally similar to the 1-norbornyl ion. From structural considerations, it would appear that 3 should be more strained, and, hence, solvolyze slower.

Table 2. Relative Solvolytic Reactivity of Bridgehead Bromides.[a]

R	Rel. Rate
Tert.-butyl	1.0
1-Adamantyl	10^{-3}
1-Bicyclo[2.2.2]octyl	10^{-6}
1-Norbornyl	10^{-13}
Cubyl	10^{-40}[b]

a Taken from reference 9, p. 299.

b Calculated (See references 10 and 11).



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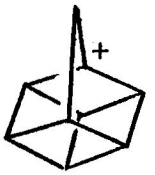


3

Direct evidence of the relative stability of ions 2 and 3 by conventional methods is difficult to obtain. Derivatives of these compounds solvolyze too slowly to provide meaningful solvolytic data. The work described in part I of this thesis is directed toward evaluating the use of mass spectrometry to provide quantitative data on relative carbonium stability for these two rigid systems and for strained bicyclic systems in general.

RESULTS AND DISCUSSION

The basic conclusion from the work of Dejongh and Shrader[4-7] and an analysis of the mass spectral data for a series of simple alkyl bromides shown in Table 1 is that relative carbonium stabilities as determined by mass spectrometry parallels carbonium ion stability as measured by solvolytic studies. This result was of particular importance in small ring chemistry since it could afford a method for assessing cation stabilities for strained systems where solvolysis data are not available. To confirm the reliability of the mass spectral method in our laboratories, mass spectra for a series of simple alkyl and cycloalkyl bromides were taken and the ratio of the intensities of the parent-Br ion relative to the parent ion were recorded (Table 3).

Table 3. [M - Br]/[M] Ratios for Some Selected Bromides.

COMPOUND	RATIO
1-Bromopropane	4.94 ± 0.03
1-Bromobutane	6.98 ± 0.17
1-Bromopentane	7.48 ± 0.13
1-Bromohexane	5.18 ± 0.1
1-Bromoheptane	0.26 ± 0.06
2-Bromopropane	6.21 ± 0.07
2-Bromobutane	41.11 ± 0.84
Cyclopropyl Bromide	7.15 ± 0.05
Cyclobutyl Bromide	37.99 ± 1.04
Cyclopentyl Bromide	41.67 ± 1.0
Cyclohexyl Bromide	20.75 ± 0.43

For the series studied, the general trend of carbonium stability pertains, with the exception of 2-bromopropane which showed a relative weak ion corresponding to loss of a bromine atom. The small value for cyclopropyl bromide is consistent with the decreased stability of the cyclopropyl cation relative to that for cyclobutyl and cyclopentyl. Adamantyl and tertiary-butyl bromides were also studied, but these showed no discernible parent ions, even when the ionization voltage was reduced to 15 eV. The DuPont 21-490 Mass Spectrometer used to determine the mass spectra typically gives smaller parent ion peaks than usual. The enhanced intensity of the parent-Br ion in the mass spectra of adamantyl and tertiary-butyl bromides over those observed for the compounds in Table 3 is consonant with the greater stability of these tertiary ions.

The mass spectrum of 1-norbornyl bromide (1) is shown in Figure 1 and the tabulated spectrum is presented in Table 4.

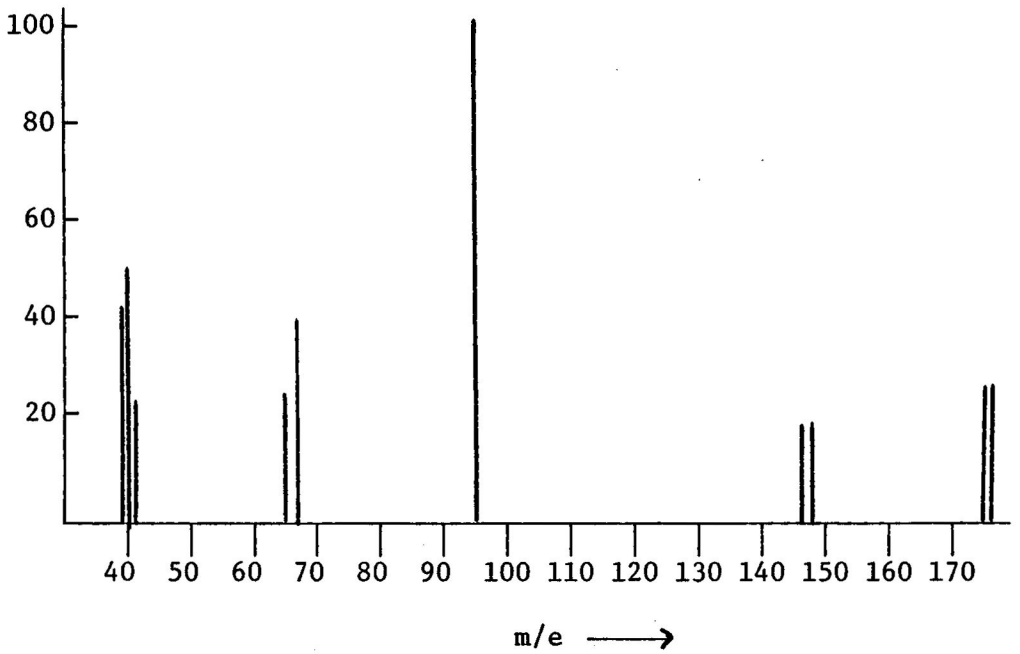


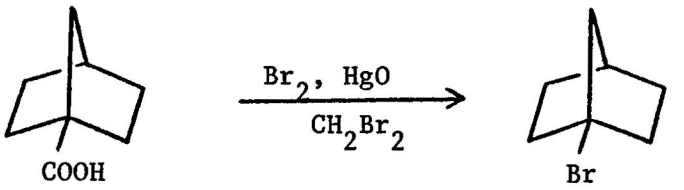
Fig. 1. Mass Spectrum of 1-Norbornyl Bromide.

Table 4. Mass Spectral Data for 1-Norbornyl Bromide.

m/e	Rel. Intensity (%)	Formula
39	41	$C_3H_3^+$
40	49	$C_3H_4^+$
41	23	$C_3H_5^+$
65	25	$C_5H_5^+$
67	39	$C_5H_7^+$
95	100	$C_7H_{11}^+$
146	22	$C_5H_{79}Br^+$
148	22	$C_5H_{81}Br^+$
174	29	$C_7H_{79}Br^+$
176	28	$C_7H_{81}Br^+$

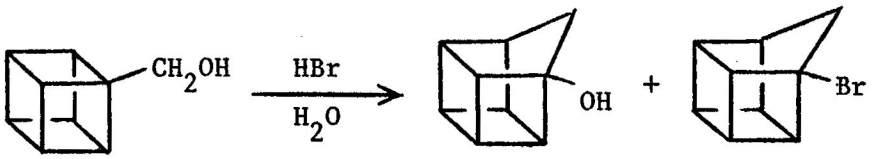
The major fragmentation path involves loss of bromide and elimination of ethylene from the parent ion as competing processes. It is particularly interesting to note the intensity of the base peak [M - Br] relative to the parent. The measured ratio of 3.4 corresponds to that for primary carbonium ions, and thus, reflects the instability of the 1-norbornyl cation.

1-Norbornyl bromide was prepared from 1-norbornyl carboxylic acid[12] using the Cristol Firth modification of the Hunsdieker reaction as described by Luh.[10]



4 1

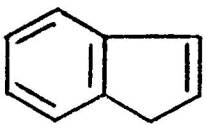
Homocubyl bromide (7), the second compound required for this study, was prepared as reported previously.[13]



5 6 7

The mass spectrum of homocubyl bromide shows the characteristic pattern for the isotopic cluster for bromine with a parent ion at m/e 196 (Figure 2).[14] Contrary to expectation, this ion intensity was extremely weak (less than 1%) compared to the base peak at m/e 117, an especially stable cation. Although the structure of this ion is not known with certainty, it clearly cannot correspond to the homocubyl ion formed by simple loss of a bromine atom from the parent ion. Interestingly, this ion appears in the mass spectra of a variety of C_9H_9X derivatives including homocubyl alcohol (6) and cubylcarbinyl alcohol (5). McEwen has made a tentative assignment of this species to an indene derivative (8), presumably formed by rearrangement of the unstable homocubyl cation followed by a proton shift.[15] Attempts to further

characterize this ion are in progress.



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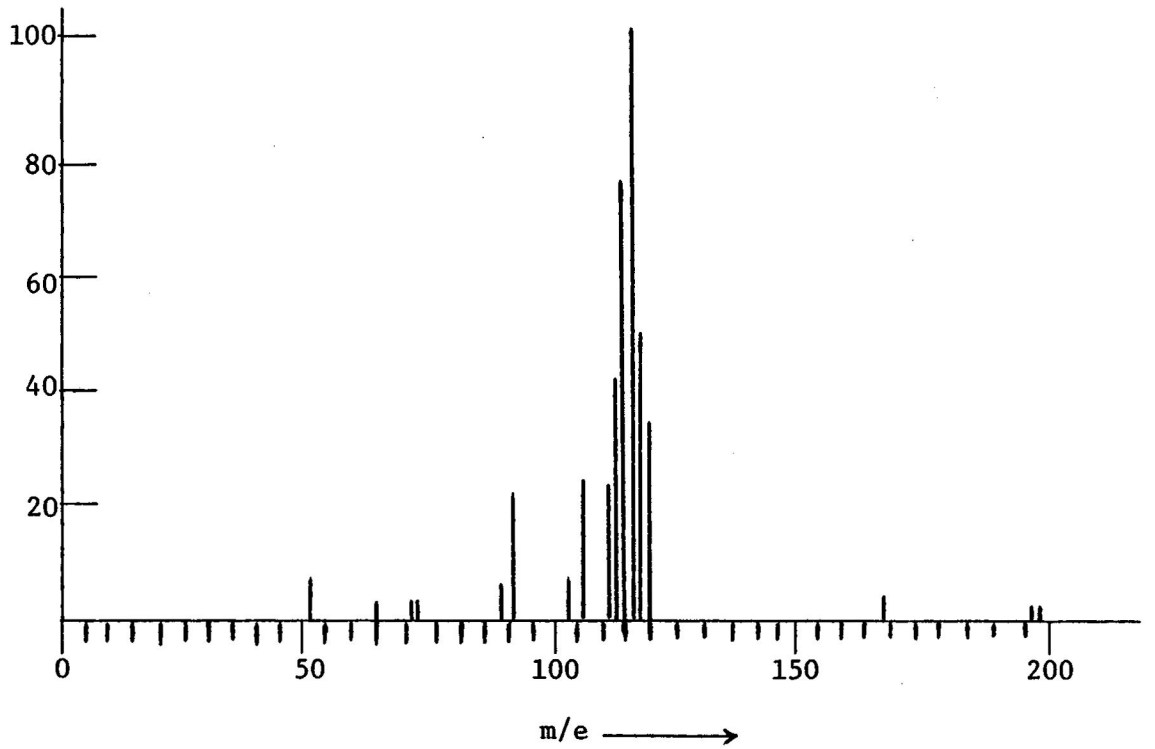


Fig. 2. Mass Spectrum of Homocubyl Bromide.

The preliminary conclusion from the mass spectral data indicates that the desired correlation between mass spectral fragmention patterns and solvolysis does not hold for all systems. This appears particularly

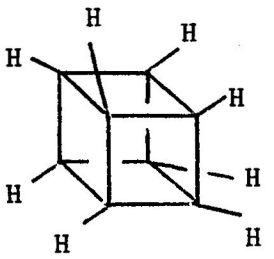
true for compounds in the cubane and homocubane series where the potential bridgehead cation is too strained and subsequent rearrangement occurs to yield a more stable species. A similar observation was made for the fragmentation of 1-norbornyl bromide. Thus, the utility of the proposed method applies only to those comparisons in which the same (or very similar) ion is produced in the initial fragmentation process.

PART II

MASS SPECTRA OF CUBANE DERIVATIVES

INTRODUCTION

Cubane (9) is a saturated hydrocarbon constructed of eight methine carbon atoms bound together symmetrically in the form of a cube. It is an especially interesting molecule because of its cubic structure, high



9

symmetry (O_h point group) and fascinating chemistry. This hydrocarbon (pentacyclo[4.0.$0^{2,5}$.$0^{3,8}$.$0^{4,7}$]octane) has nine symmetry planes, a center of symmetry and a dihedral angle of 180,[16] four C_{3v} methane (CCC=90) and a total strain energy of 155 kcal/mole.[17]

Since the first successful synthesis of this highly strained polycyclic compound, it has held the attention of many chemists. This thesis describes one of the first attempts to characterize the major fragment ions of cubane derivatives by mass spectrometry.

RESULTS AND DISCUSSION

The cubane derivatives used for the mass spectral studies were prepared according to Scheme II without modification.[13] The mass spectra were determined via direct injection probe at an oven temperature of 250° and probe temperature of 150°.

CUBYLCARBINOL

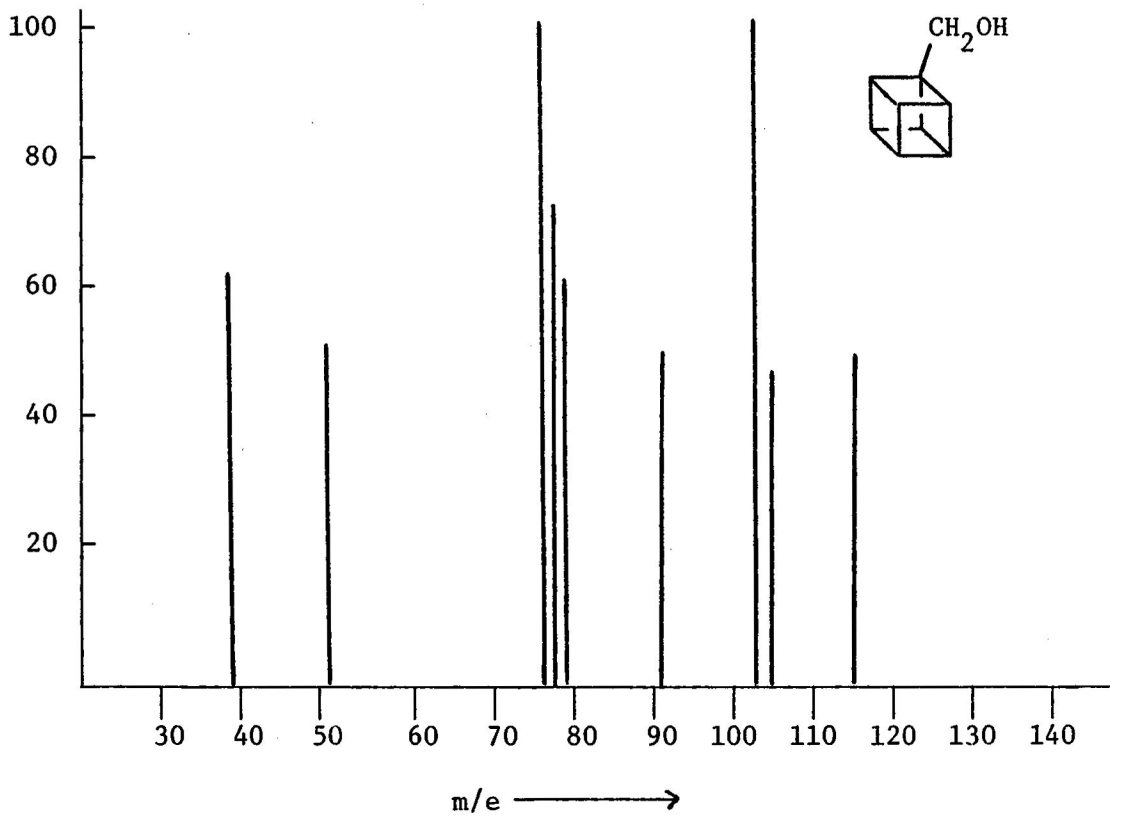
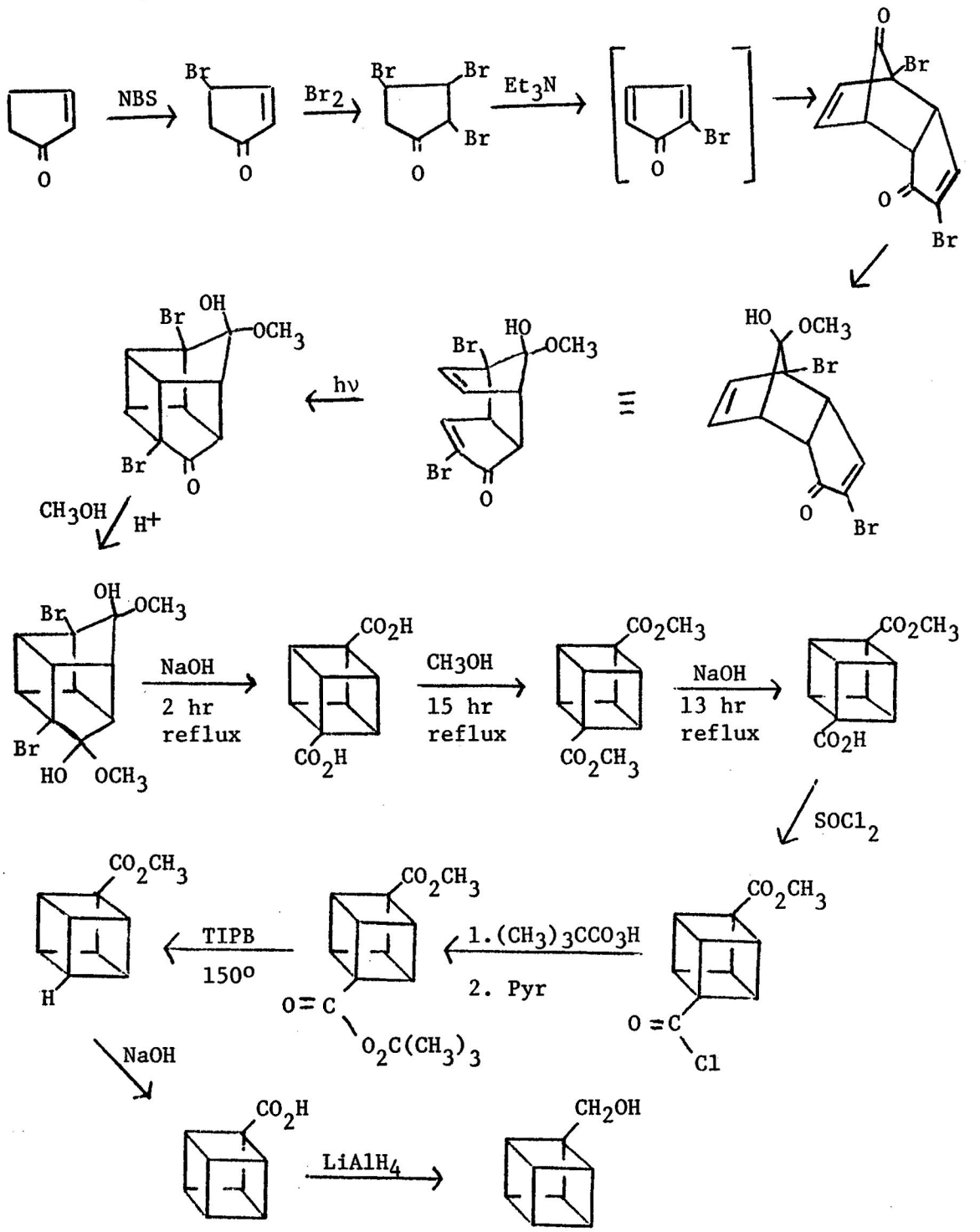


Fig. 3. Mass Spectrum of Cubylcarbinol.

The mass spectrum of cubylcarbinol is shown in Figure 3 and tabulated in Table 4. The base ($C_8H_7^+$) peak can be attributed to the loss of $\cdot CH_2OH$ at m/e 103. The common fragments lost are $\cdot CH_2OH$ (M-31), $\cdot OH$ (M-17), H_2O (M-18), and loss of C_3H_3 from the m/e 117 species followed

SCHEME II


NBS
Br2
Et3N
hν
CH3OH
H+
NaOH
2 hr
reflux
CH3OH
15 hr
reflux
NaOH
13 hr
reflux
SOCl2
TIPB
150°
1.(CH3)3CCO3H
2. Pyr
NaOH
LiAlH4

by successive losses of hydrogen atoms.

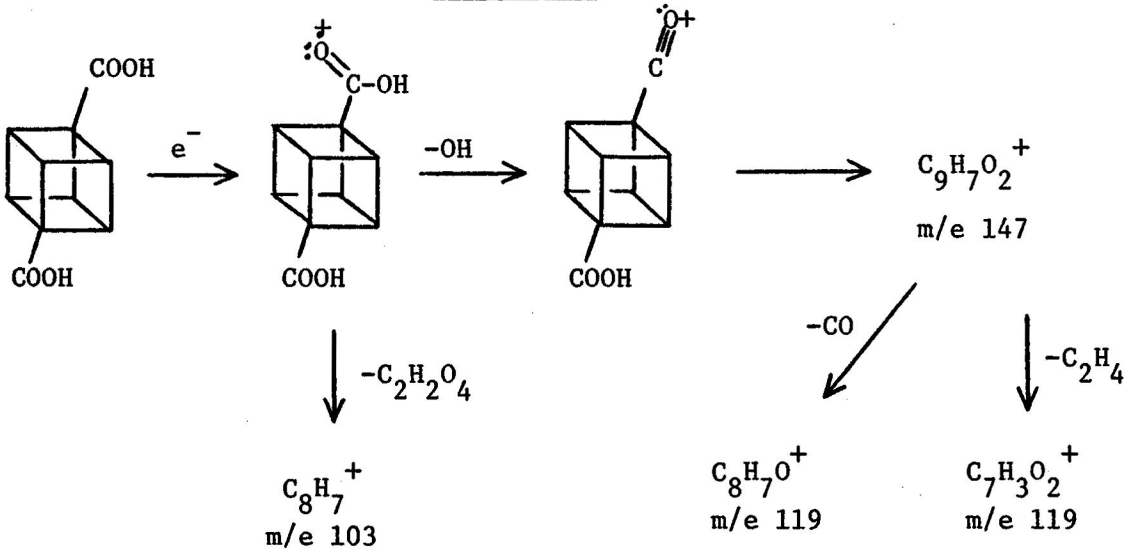
Table 5. Mass Spectral Data for Cubylcarbinol.

m/e	Relative Intensity	Assigned Formula
39	61.5%	$C_3H_3^+$
51	49.8%	$C_4H_3^+$
77	99.26%	$C_6H_5^+$
78	74%	$C_6H_6^+$
79	61.5%	$C_6H_7^+$
91	52.7%	$C_7H_7^+$
103	100%	$C_8H_7^+$
105	46.5%	$C_7H_5O^+$
115	50.5%	$C_9H_7^+$

DICARBOXYCUBANE

The molecular ion peak of a carboxylic acid is weak but usually discernible. The loss of CO_2 often occurs in the fragmentation of dicarboxylic and substituted acids which can arise from thermal decarboxylation. Through cleavage, acids can lose M-OH, but with little abundance.[18] In the spectrum of dicarboxycubane (Figure 4, Table 6) COOH is lost immediately (probably thermal decarboxylation) to give an ion m/e 147. The base peak m/e 103 can be attributed to the cubane fragment ($C_8H_7^+$) as shown in Scheme III.

SCHEME III



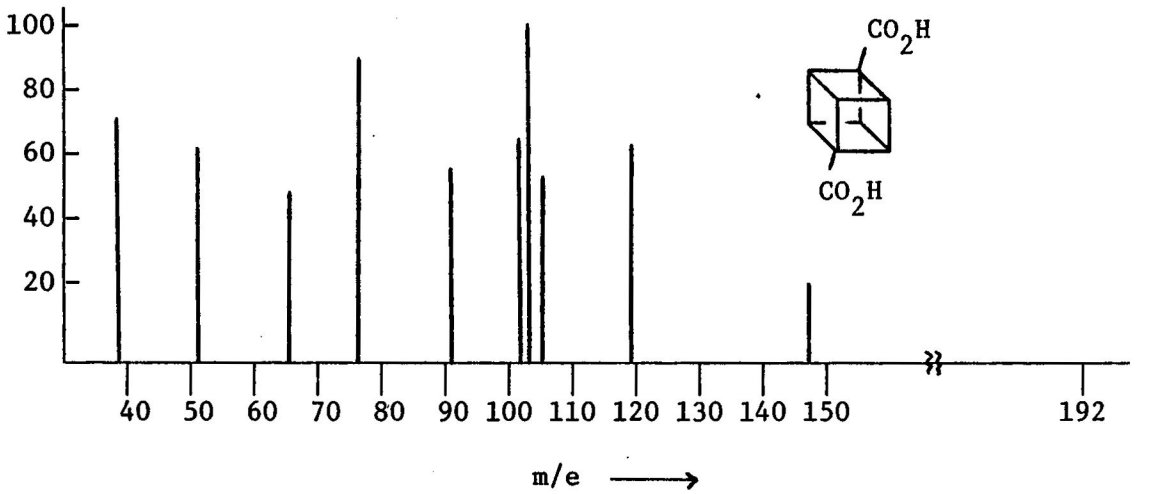


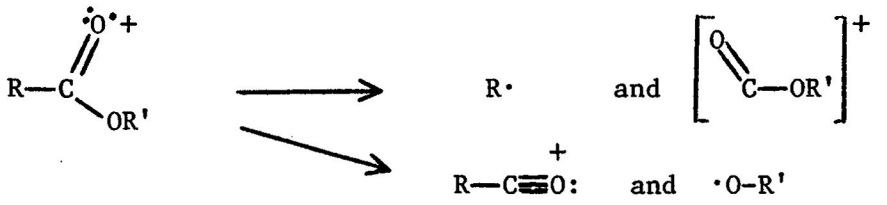
Fig. 4. Mass Spectrum of Dicarboxycubane.

Table 6. Mass Spectral Data for Dicarboxycubane.

m/e	Relative Intensity	Assigned Formula
39	69.4%	$C_3H_3^+$
51	61%	$C_4H_3^+$
65	46.3%	$C_5H_5^+$
77	91%	$C_6H_5^+$
91	56%	$C_7H_7^+$
102	62%	$C_8H_6^+$
103	100%	$C_8H_7^+$
105	46.3%	$C_7H_5O^+$
119	65%	$C_8H_7O^+$
147	21.6%	$C_9H_7O_2^+$

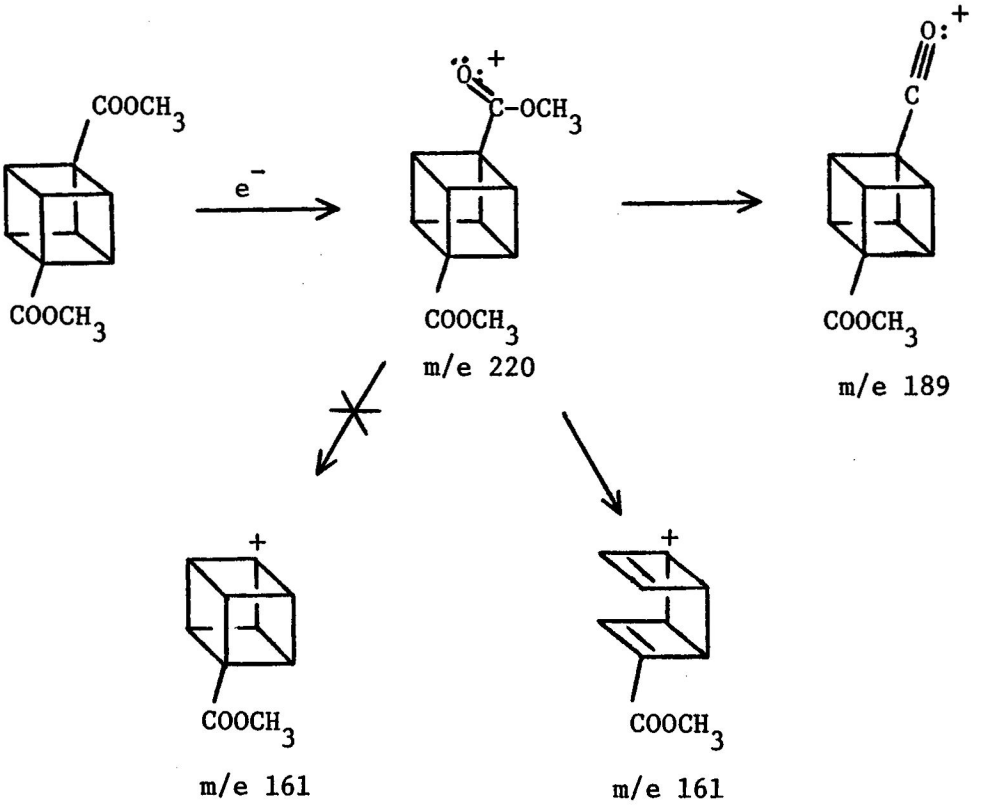
DICARBOMETHOXYCUBANE

The molecular ion peak of a methyl ester is quite distinctive (Fig. 5). Usually, cleavage occurs one bond removed from the C=O group. Four ions can result from bond cleavage next to C=O, to give the ion fragment $R\text{-}C{\equiv}O^+$, characteristic of all esters. The ions $[OR']^+$ and $[CO_2R']^+$ are usually of little importance. The latter is discernible when $R'=CH_3$ at m/e 59.



In the spectra of dicarbomethoxycubane (Fig. 5, Table 7) and cubane half-acid ester, fragments common to both are present, almost with the same intensities relative to their base peak (m/e 132); for instance, ions at m/e 51, 59, 77, 102, 105, 160, 161, and 189 as shown in Tables 7 and 8. The spectrum of dicarbomethoxycubane shows initially the loss of M-OCH_3 (m/e 189), then the loss of ·CO to form perhaps the more stable allylic carbonium ion, and, with loss of an ethylene bridge, forms the base peak at m/e 132 (Scheme 4). The spectrum of cubane half-acid ester (Fig. 6, Table 8) is closely related to dicarbomethoxycubane, except for ions at m/e 115, 118 and 128. Other carboxycubane derivatives show the same basic fragmentation pattern (with the exception of different base peaks) as the dicarbomethoxycubane and cubane half-acid ester and are presented on the following pages without discussion (Fig. 7-9, Tables 9-11).

SCHEME IV



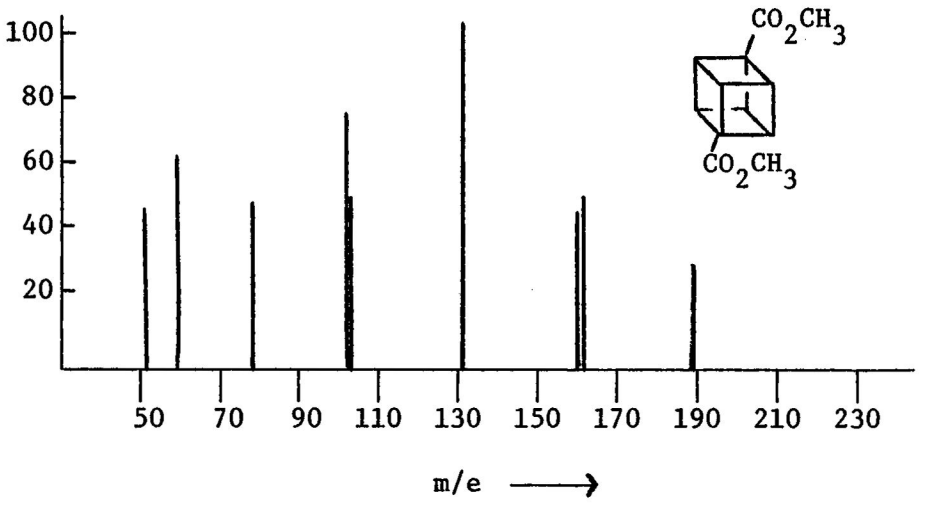


Fig. 5. Mass Spectrum of Dicarbomethoxycubane.

Table 7. Mass Spectral Data for Cubane Diester.

m/e	Relative Intensity	Assigned Formula
51	43%	$C_4H_3^+$
59	61%	$C_2H_3O_2^+$
77	45%	$C_6H_5^+$
102	70.8%	$C_8H_6^+$
105	51%	$C_7H_5O^+$
132	100%	$C_8H_4O_2^+$
160	42.5%	$C_{10}H_8O_2^+$
161	44%	$C_{10}H_9O_2^+$
189	26.5%	$C_{11}H_9O_3^+$

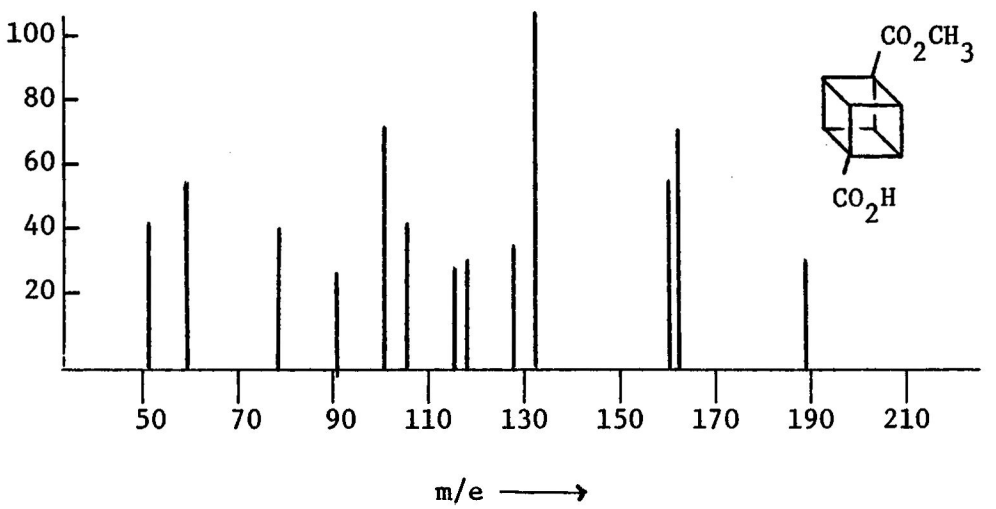


Fig. 6. Mass Spectrum of Cubane Half-Acid Ester.

Table 8. Mass Spectrum of Cubane Half-Acid Ester.

m/e	Relative Intensity	Assigned Formula
51	40%	$C_4H_3^+$
59	53%	$C_2H_3O_2^+$
77	39%	$C_6H_5^+$
91	27%	$C_7H_7^+$
102	72%	$C_8H_6^+$
105	41%	$C_7H_5O^+$
115	31%	$C_9H_7^+$
118	34%	$C_8H_6O^+$
128	37%	$C_8H_4O^+$
132	100%	$C_8H_4O_2^+$
160	52%	$C_{10}H_8O_2^+$
161	66%	$C_{10}H_9O_2^+$
189	28%	$C_{11}H_9$

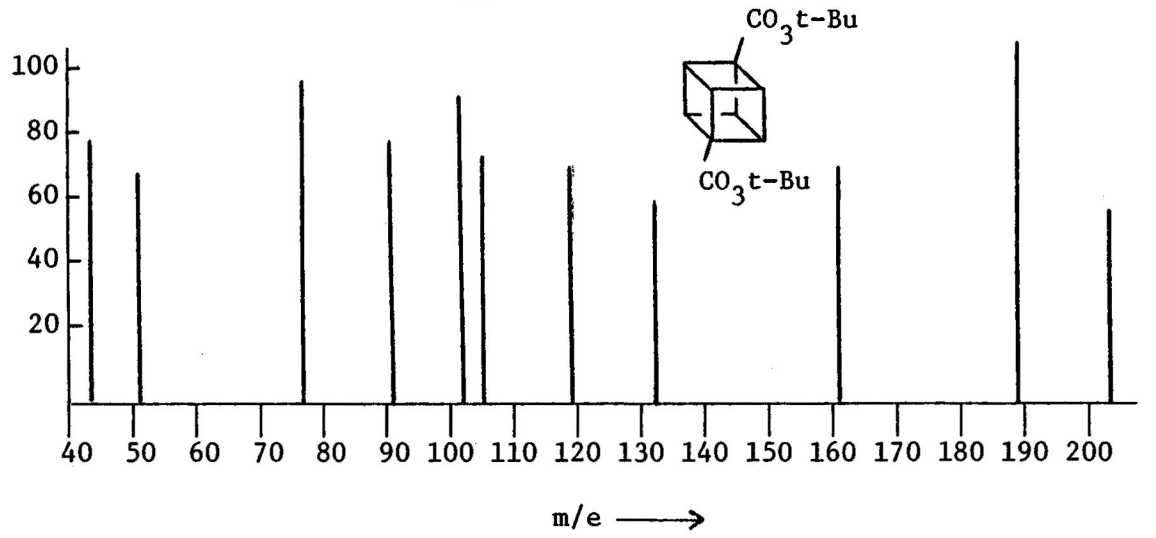


Fig. 7. Mass Spectrum of Cubane-Perester.

Table 9. Mass Spectral Data for Cubane-Perester.

m/e	Relative Intensity (%)	Assigned Formula
43	78.0	$C_3H_7^+$
51	53.8	$C_4H_3^+$
77	91.0	$C_6H_5^+$
91	77.2	$C_7H_7^+$
102	88.3	$C_8H_6^+$
105	70.1	$C_7H_5O^+$
119	65.5	$C_8H_7O^+$
133	55.86	$C_8H_5O_2^+$
161	65.5	$C_9H_5O_3^+$
189	100.0	$C_{10}H_5O_4^+$
204	51.0	$C_{11}H_8O_4^+$

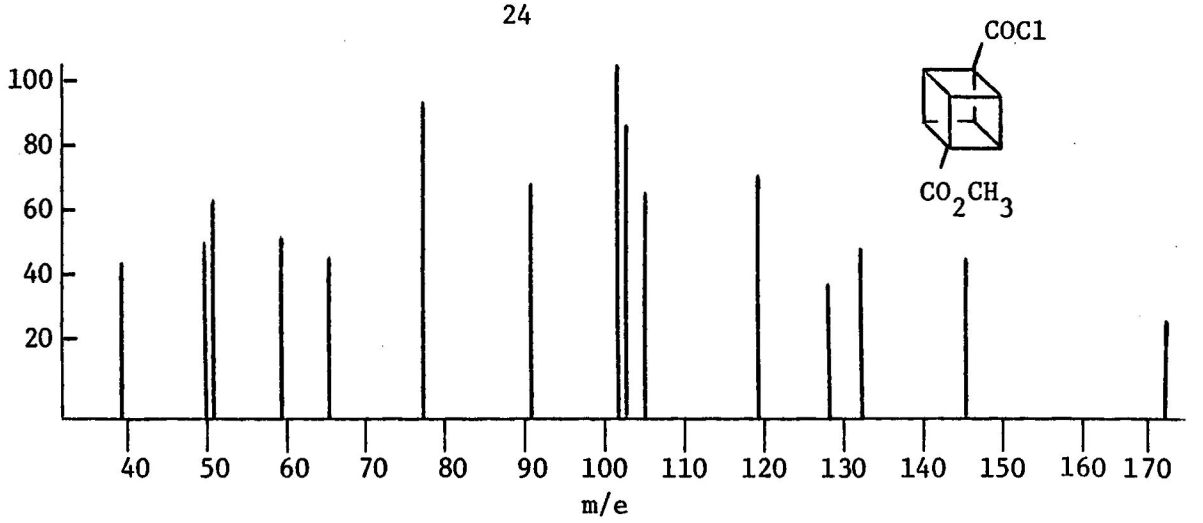


Fig. 8. Mass Spectral of Cubane Acid-Chloride-Ester.

Table 10. Mass Spectral Data for Cubane Acid-Chloride-Ester.

m/e	Relative Intensity	Assigned Formula
39	45%	$C_3H_3^+$
50	49%	
51	63%	$C_4H_3^+$
59	53%	$C_2H_3O_2^+$
65	45%	$C_5H_5^+$
77	97%	$C_6H_5^+$
91	64%	$C_7H_7^+$
102	100%	$C_8H_6^+$
103	84%	$C_8H_7^+$
105	63%	$C_7H_5O^+$
119	74%	$C_8H_7O^+$
128	36%	$C_9H_4O^+$
132	50%	$C_8H_4O_2^+$
145	36%	$C_9H_5O_2^+$
173	26%	$C_{11}H_9O_2$

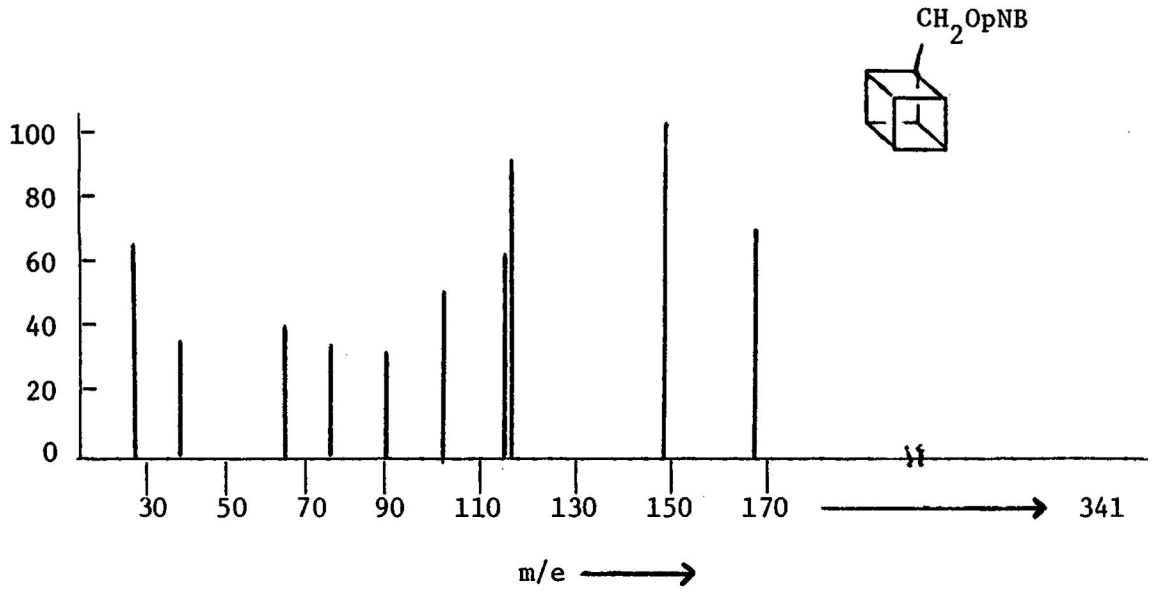


Fig. 9. Mass Spectrum of Cubane para-Nitrobenzoate Ester.

Table 11. Mass Spectral Data for Cubane para-Nitrobenzoate Ester.

m/e	Relative Intensity	Assigned Formula
29	63%	$C_2H_5^+$
39	35%	$C_3H_3^+$
65	39%	$C_5H_5^+$
76	37%	$C_6H_4^+$
91	37%	$C_7H_7^+$
103	50%	$C_8H_7^+$
114	61%	$C_9H_6^+$
115	91%	$C_9H_7^+$
149	100%	$C_7H_3NO_3^+$
167	24%	$C_7H_5NO_4^+$

EXPERIMENTAL

All mass spectra were recorded on a DuPont 21-490 Mass Spectrometer operating at 70eV. The mass spectrometer was interfaced with a Varian Aerograph Model 1400 gass chromatograph and a Varian CDS 101 Data System.

Perfluorokerosene (low and high boiling) and perfluorotributylamine were chosen to calibrate the mass marker. Two microliters each of the alkyl bromides were injected into the batch inlet system and into an evacuated reservoir from which they flowed through a molecular leak into the ion source at nearly a constant rate. The spectrum was recorded on a Bell and Howell oscillograph. Source temperature was 150°. Higher source temperatures gave poorer reproducibility.

Samples were obtained from Eastman and Aldrich Chemical Companies. 1-Norbornylbromide and 1-homocubylbromide were prepared by methods reported previously.[10-13] They were analyzed as mixtures by introduction through the gas chromatograph using a 10 ft 2% OV-17/1% OV-210 column on 100/120 Supelcoport programmed at 6°/min from 60-150°.

REFERENCES

1. F. W. McLafferty, "Interpretation of Mass Spectra," 2nd Ed., W. A. Benjamin, Inc., New York, N.Y., 1973.

2. H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Mass Spectrometry of Organic Compounds," Holden-Day, San Francisco, CA, 1967.

3. E. Stenhagen, S. Abrahamson, and F. McLafferty, "Atlas of Mass Spectral Data," Wiley-Interscience, New York, N.Y., 1969, Vol. 1.

4. D. C. DeJongh and S. R. Shrader, J. Amer. Chem. Soc., 88, 3881 (1969).

5. M. M. Bursey and F. W. McLafferty, ibid., 529 (1966).

6. M. M. Bursey and F. W. McLafferty, ibid., 4484 (1966).

7. D. C. DeJongh, S. R. Shrader, R. G. Isakson and N. A. LeBel, Org. Mass Spectrom., 2, 919 (1969) and references cited therein.

8. W. J. LeNoble, "Highlights of Organic Chemistry," Marcel Dekker, New York, N.Y., 1974, pp. 690-695.

9. R. C. Fort, Jr. and P. von R. Schleyer, in "Advances in Alicyclic Chemistry," H. Hart and G. J. Karabatsos, Eds., Academic Press, New York, N.Y., 1966, p. 299, Vol. 1.

10. T.-Y. Luh, Ph.D. Dissertation, University of Chicago, Chicago, Ill., 1974.

11. No solvolytic data on cubane derivatives are available. However, the relative reactivity of this compound is estimated based on the calculations using the modified Westheimer model: Cf. G. L. Gleigher and P. von R. Schleyer, J. Amer. Chem. Soc., 89, 582 (1967).

12. Supplied by Professor D. E. Applequist, University of Illinois.

13. (a) T. W. Cole, Jr., Ph.D. Dissertation, University of Chicago, Chicago, Ill., 1966; (b) C. N. McEwen, M. S. Thesis, Atlanta University, Atlanta, GA, 1970; (c) H. C. Ashline, M. S. Thesis, Atlanta University, Atlanta, GA, 1970.

14. Spectrum determined by T. Cole.

15. C. N. McEwen, private communications to T. Cole, September, 1977.

16. E. B. Fleisher, J. Amer. Chem. Soc., 86, 3889 (1964).

17. Schaefer, H. F., III, "Applications of Electronic Structure Theory," Plenum Press, New York, N.Y., 1977, p. 245.

18. S. R. Shrader, "Introduction to Mass Spectrometry," Allyn and Bacon, Boston, 1971.